This work has been submitted for publication in Space Weather

# WASAVIES: Warning System for Aviation Exposure to Solar Energetic Particles

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Space Weather Workshop 2014 @ Boulder CO on 8-11 April 2014

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- Development of WASAVIES
  - 3. Interplanetary SEP transport (Kubo)
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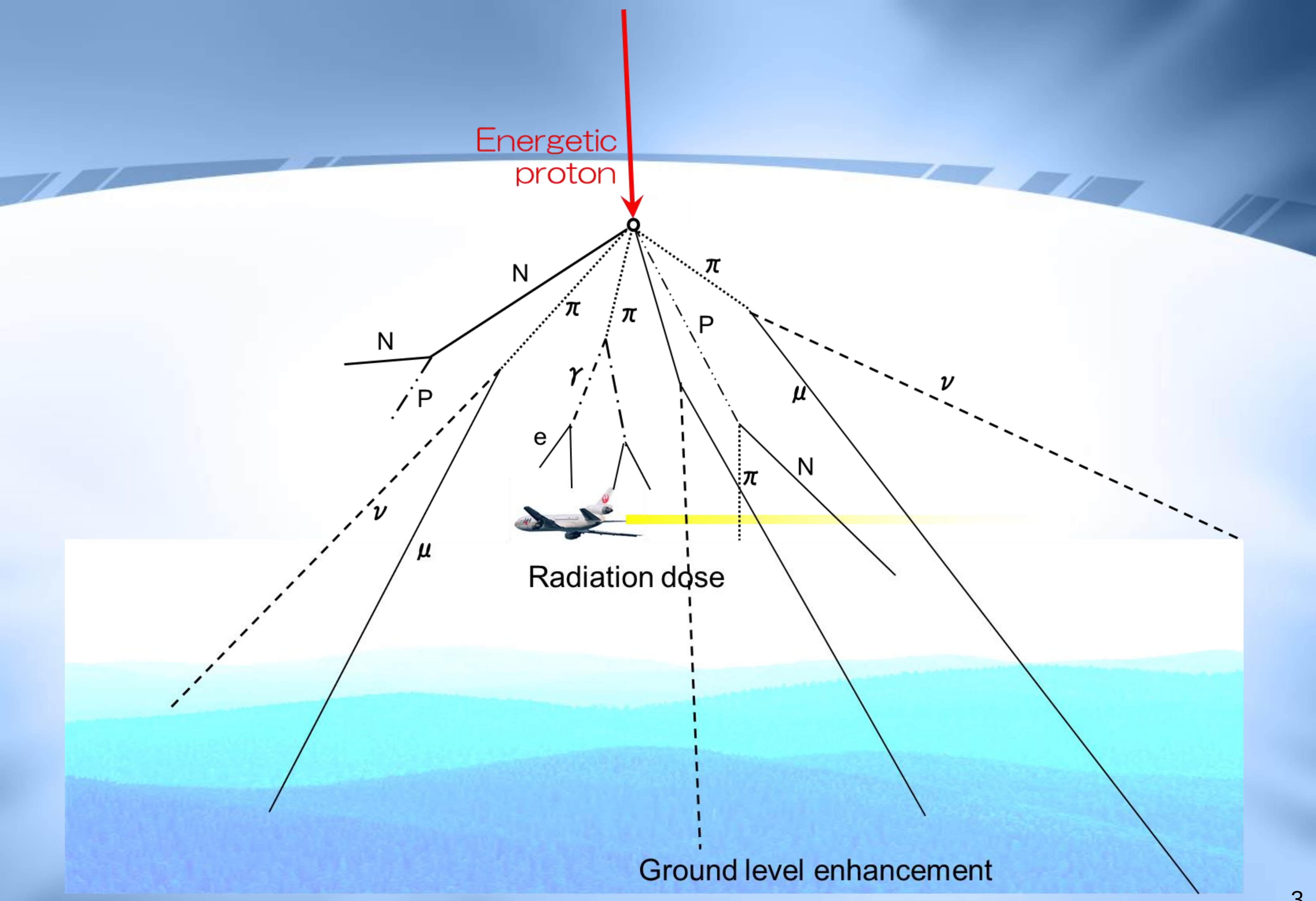
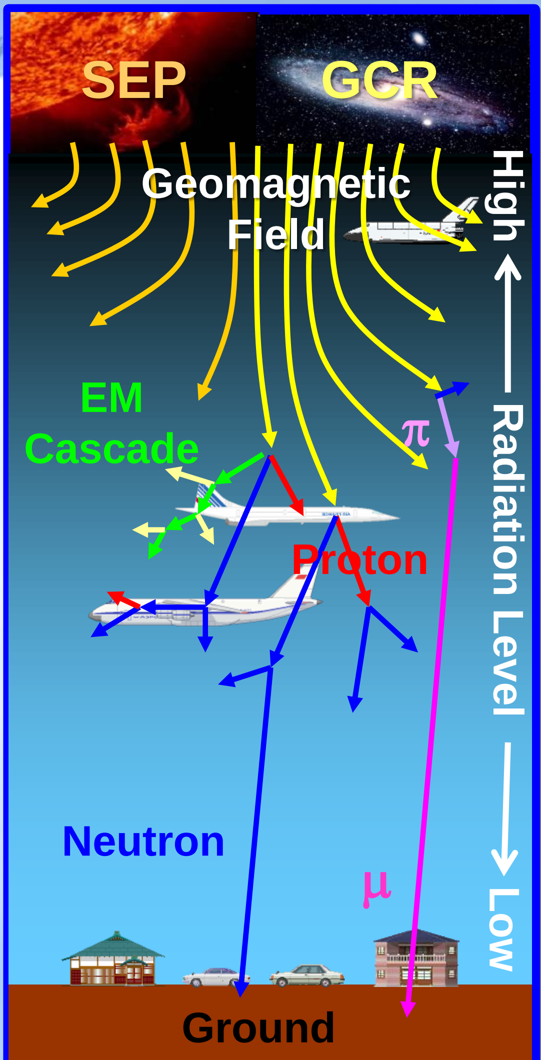
  - 5. Air-shower simulation (Sato)
- Preliminary Results of WASAVIES
- Summary and Future



Energetic proton
N
N
P
π
π
π
P
γ
e
μ
ν
μ
ν
π
N
Radiation dose
Ground level enhancement

# Aircrew exposure by SEP and GCR




Motion of cosmic-ray in the Atmosphere

| Solar Energetic Particle | Galactic Cosmic-Ray |
|---|---|
| **The Sun** Accelerated by solar flare and CME | **Galaxy** Accelerated by supernova remnants |
| **Interplanetary** Focused transport | **Heliosphere** Modulated by solar wind |

**Geomagnetic Field**
Change direction, reflected / penetrate

**Suddenly & High dose rates**

**Continuously & Low dose rates**

**per Atmosph**
Cause  ear interaction and generate air  wer

S  cles

**Forecast**

**Afterward Evaluation**

**Flight Altitude**
Deposit energies into human body

# Annual doses for aircrews

**Annual doses in 2007 for each pilot and cabin attendant employed by Japanese airline companies**

| | Average (mSv) | Maximum (mSv) |
|---|---|---|
| Pilot | 1.68 | 3.79 |
| Cabin Attendant | 2.15 | 4.24 |

Yasuda, Isotope News (2009)

**Annual dose limitation for aircrews in Japan is 5 mSv**

Dose per flight during the largest solar particle event can exceed a few mSv …

**Aircrew doses may exceed their limitation**

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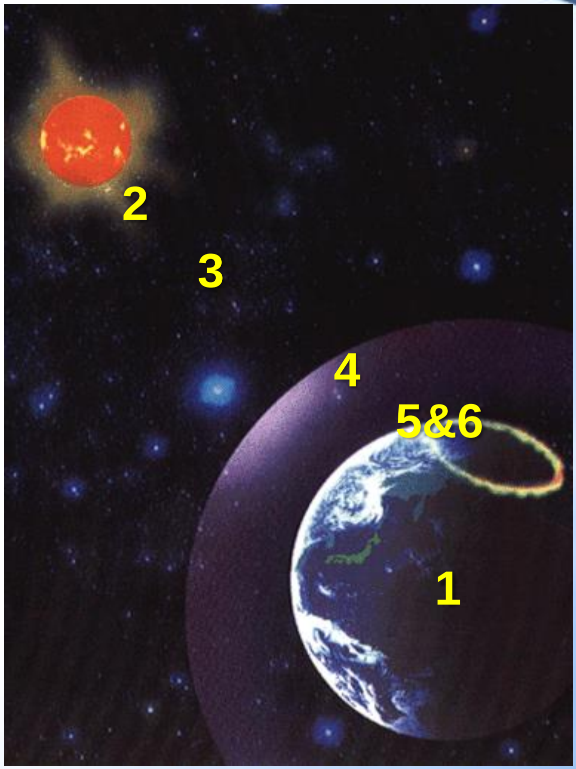
# Outline of WASAVIES

1. Detect ground level enhancement (GLE) onset by multiple ground-based neutron monitor
2. Determine the mean free path (MFP) of SEP on the basis of solar wind simulation
   Determine CME parameters such as its speed to predict the CME-driven SEP profile
3. Determine SEP flux outside the magnetosphere using the MFP and focused transport simulation
   Calculate time-varying shock-accelerated SEP spectrum
4. Calculate SEP fluxes at the top of the atmosphere at any latitude & longitude using proton trace model
5. Calculate secondary particle fluxes in the atmosphere using database developed based on air shower simulation
6. Convert their fluxes on flight routes to corresponding doses using dose-conversion coefficients



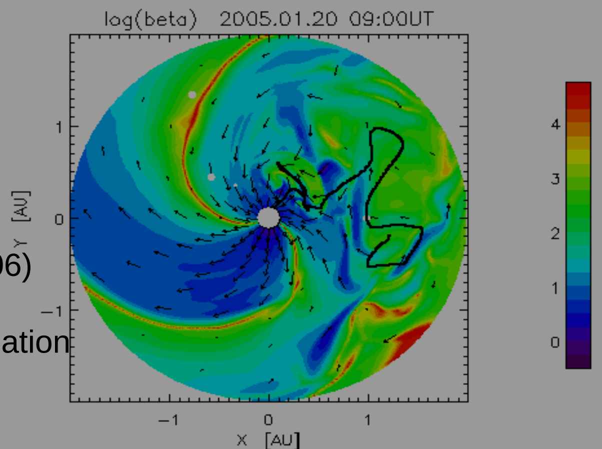

**Aim to forecast SEP doses within 2.5 hours after flare onset**

# Forward models of WASAVIES

## 1&2. GLE alarm & Solar wind

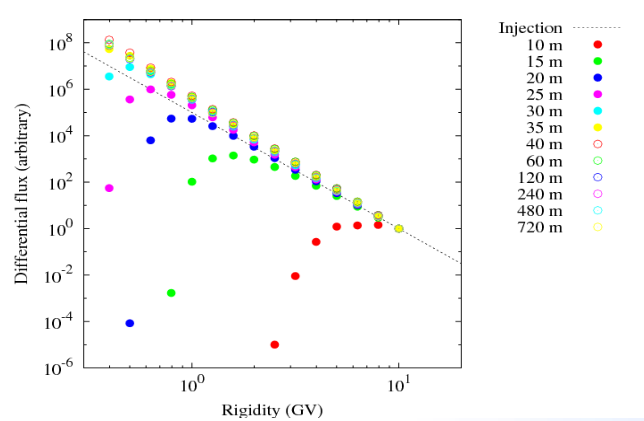
GLE Alarm
(Kuwabara+ 2006)

Solar wind simulation
(Shiota+ 2014)



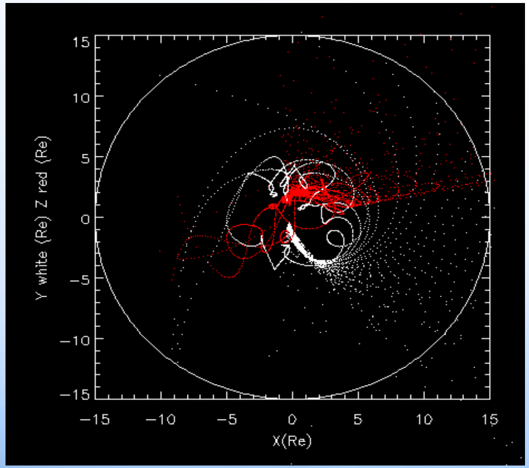

## 3. Interplanetary SEP Transport

Parker spiral
Mean free path
Injection spectra



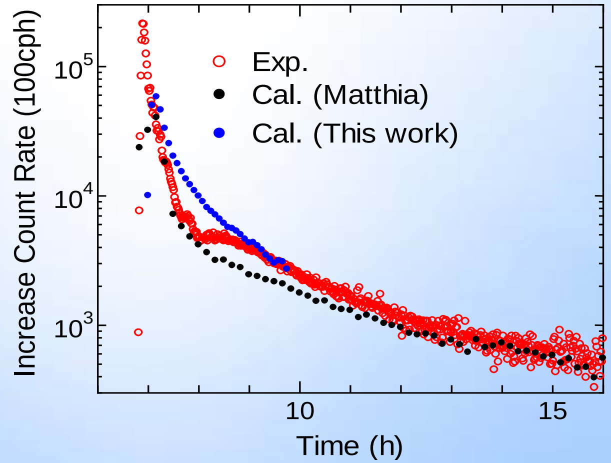

Energy spectra
(normalized)

## 4. Magnetospheric SEP trace




Energy spectra at
top of atmosphere

## 5. Air-shower (Sato+ 2013)



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# 3. Formulation of SEP transport

- 1-D (spatial) focused transport equation (FTE) with adiabatic deceleration

$$\frac{\partial f}{\partial t} + \underbrace{\mu v b_i \partial_i f}_{\text{Streaming}} + \underbrace{V_i \partial_i f}_{\text{Convection}} + \underbrace{\frac{dp}{dt}\frac{\partial f}{\partial p}}_{\text{Momentum change}} + \underbrace{\frac{d\mu}{dt}\frac{\partial f}{\partial \mu}}_{\text{Pitch angle change}} - \underbrace{\frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right)}_{\text{Pitch angle scattering}} = 0$$

- Momentum change

$$\frac{dp}{dt} = p\left[\frac{1-3\mu^2}{2} b_i b_j \partial_i V_j - \frac{1-\mu^2}{2}\partial_i V_i\right]$$

←Adiabatic deceleration by solar wind divergence

- Pitch angle change

$$\frac{d\mu}{dt} = \frac{1-\mu^2}{2}\left[\underbrace{-v b_i \partial_i (\ln B)}_{\text{Adiabatic focusing}} + \mu\big(\underbrace{\partial_i V_i - 3 b_i b_j \partial_i V_j}_{\text{Solar wind divergence}}\big)\right]$$

- Pitch angle scattering coefficient: Modified quasi-linear theory (Beeck & Wibberenz 1986, Bieber+1994)

$$D_{\mu\mu} = D_0 v R^{q-2}\{|\mu|^{q-1} + h\}(1-\mu^2)$$

q: Index of wave number spectrum of solar wind turbulence

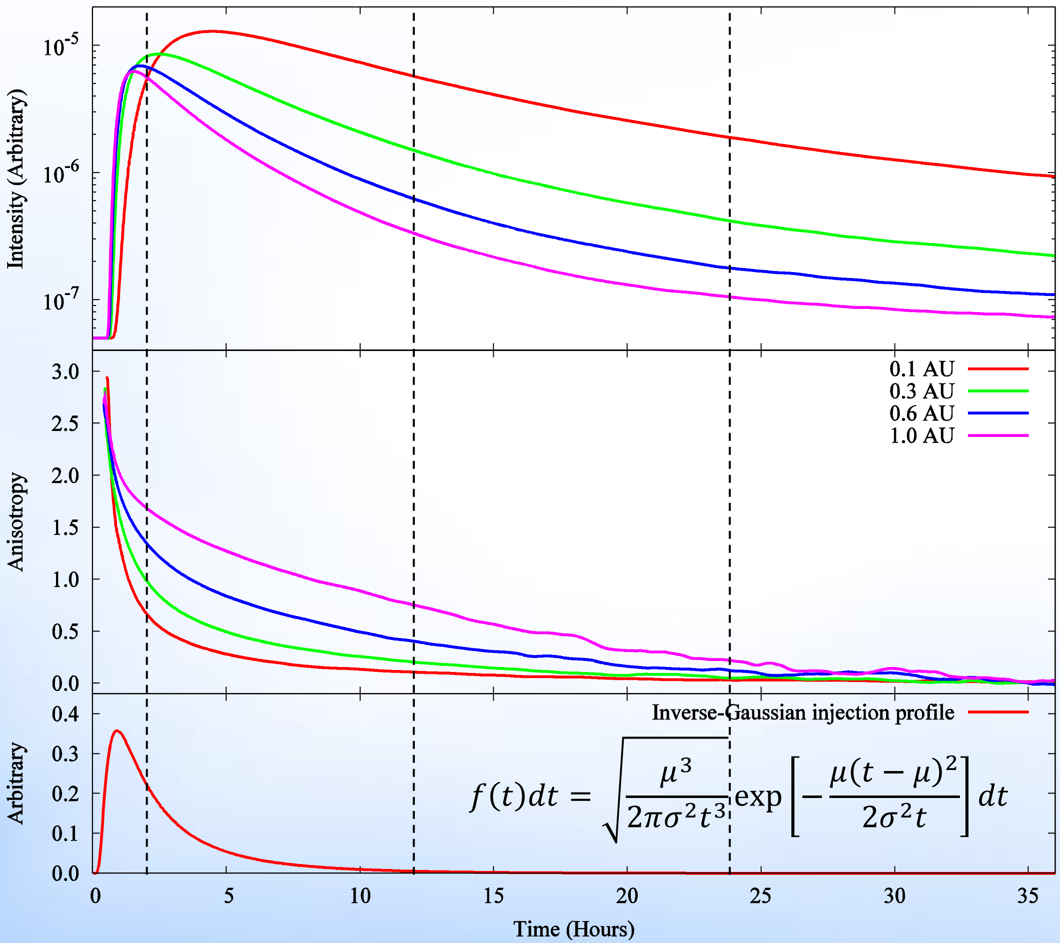
Modification to avoid no scattering at $\mu = 0$

- Mean free path

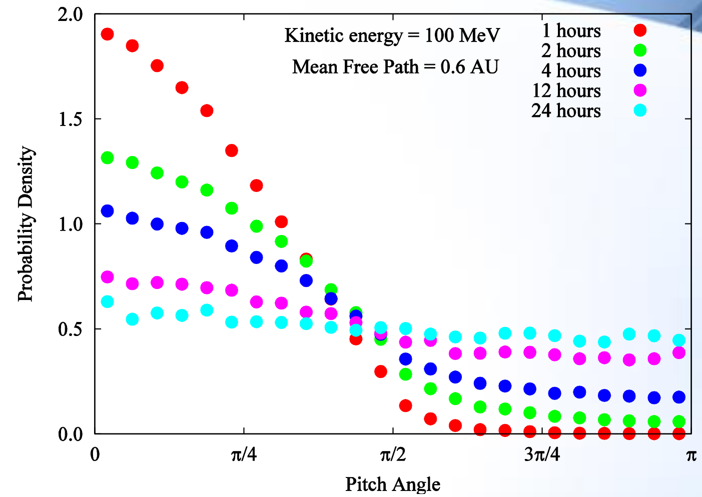
$$\lambda_\parallel = \frac{3v}{8}\int_{-1}^{1}\frac{(1-\mu^2)^2}{D_{\mu\mu}}d\mu \qquad \lambda_\parallel \cos^2\varphi \equiv \lambda_r = \text{const. (approx.)}$$

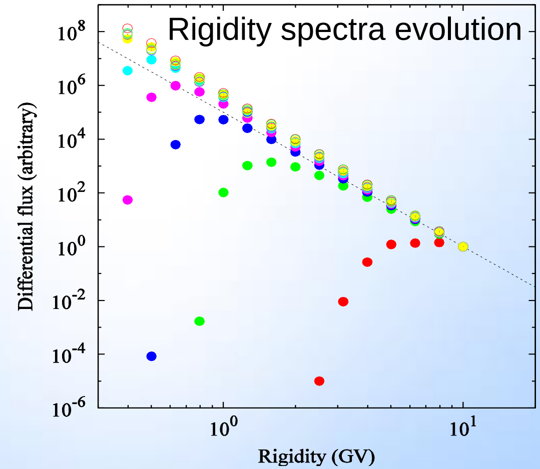
# 3. Determine SEP flux and so on

Simulated intensity (top) and anisotropy (middle) of 100MeV SEP at the Earth, and SEP injection profile near the Sun (bottom).



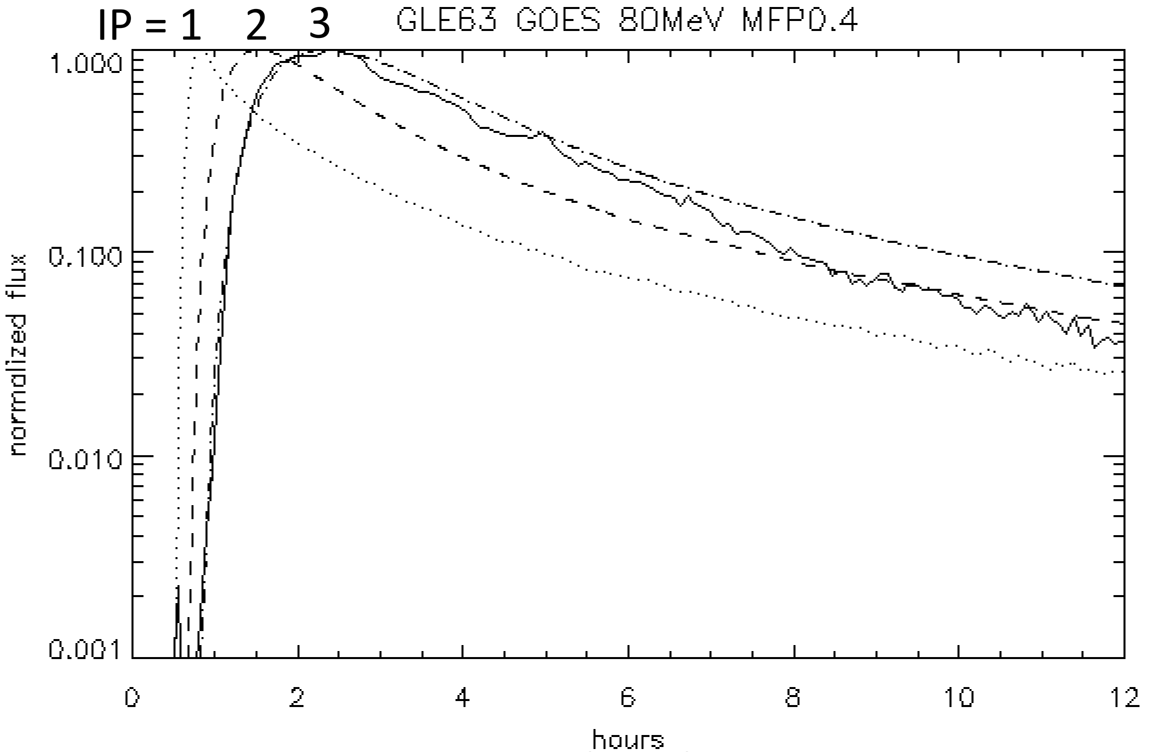

Temporal evolution of pitch angle distribution for 0.6 AU mean free path cases.



# 3. Three types of injection profiles

80 MeV proton normalized differential flux → calibrated with GOES real-time observations




GOES: solid curve

IP = 1: The most impulsive profile of GLE69 event

IP = 2: Five times longer time scale than that of GLE69 event

IP = 3: Ten times longer time scale than that of GLE69 event

Choose one of three profile by comparing 80 MeV GOES data and calculated flux

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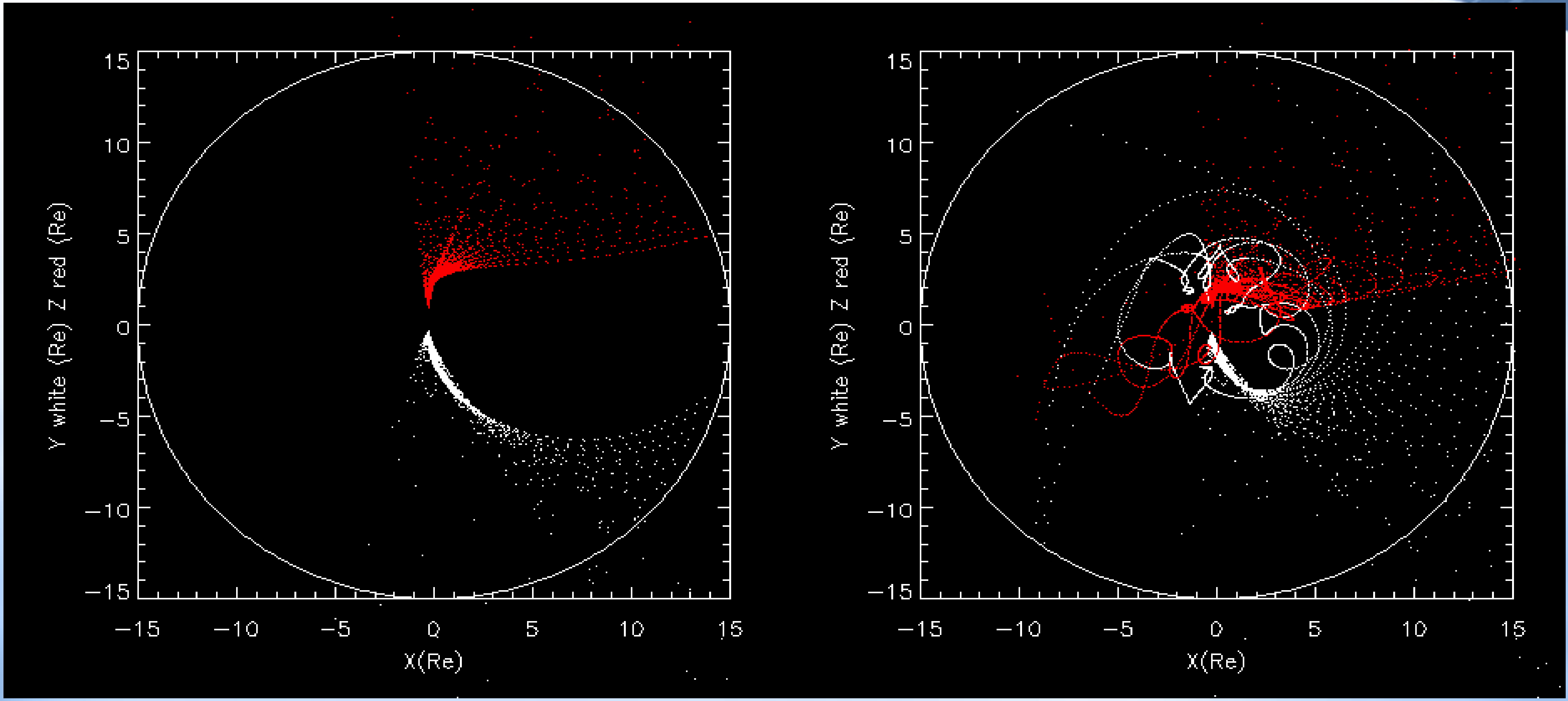
# 4. SEP transport in magnetosphere

Negatively charged protons are traced back from the top of atmosphere to outside of magnetosphere.




Tyganenko89 (2005/1/20), N65 E00 80km, 1-100 GV p-

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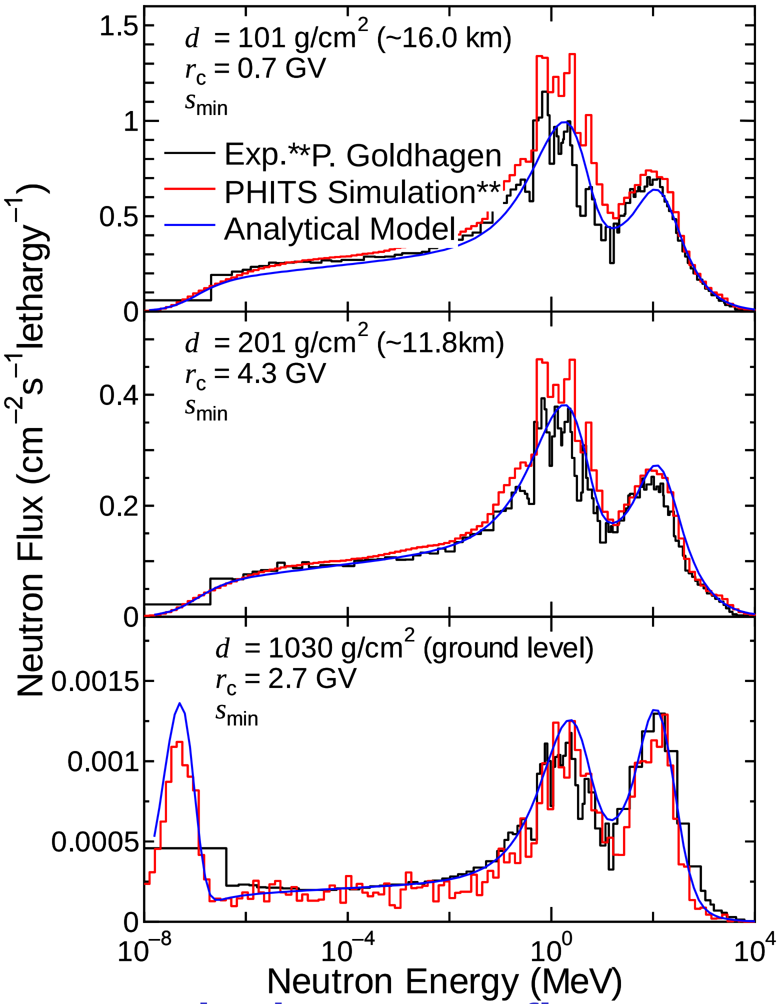
# 5. Air-shower simulation




**Atmospheric Neutron fluxes**

## Air-Shower Simulation

Reproduce the experimental data very much

**Validity of the simulation procedure, including the nuclear reaction models**

too time-consumptive …

## Analytical Model (EXPACS)

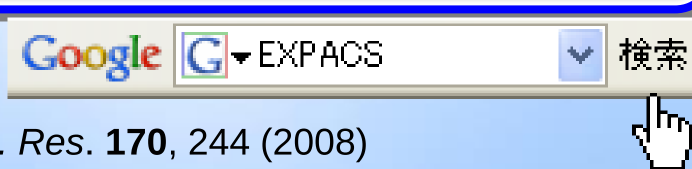
Analyzed location (altitude & geomagnetic) and time dependence of the fluxes

Proposed analytical model that can estimate <u>cosmic-ray fluxes</u> anywhere and anytime in the world**

**n, p, $\alpha$, $\mu^{+-}$, $e^-$, $e^+$, photon**

**Excellent agreement can be observed**

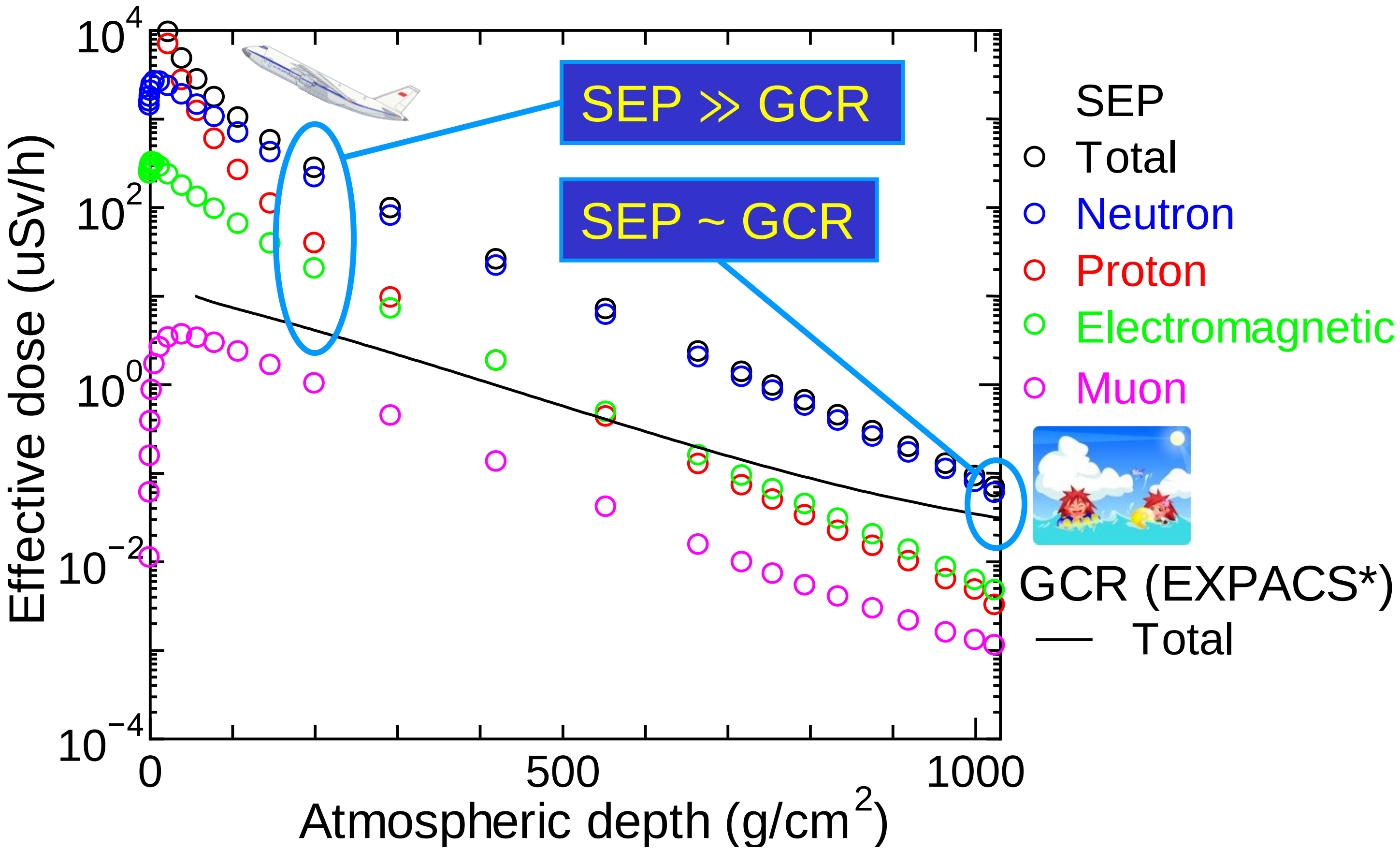
Opened to public, http://phits.jaea.go.jp/expacs/




T. Sato et al. *Radiat. Res*. **166**, 544 (2006), T. Sato et al. *Radiat. Res*. **170**, 244 (2008)

# 5. SEP dose estimation during GLE

**SEP Dose = ∫ SEP flux × Dose Conversion Coefficient**




**Dose rates above McMurdo during the peak of the GLE**

**Neutron dose is dominant at flight altitudes**

* http://phits.jaea.go.jp/expacs/

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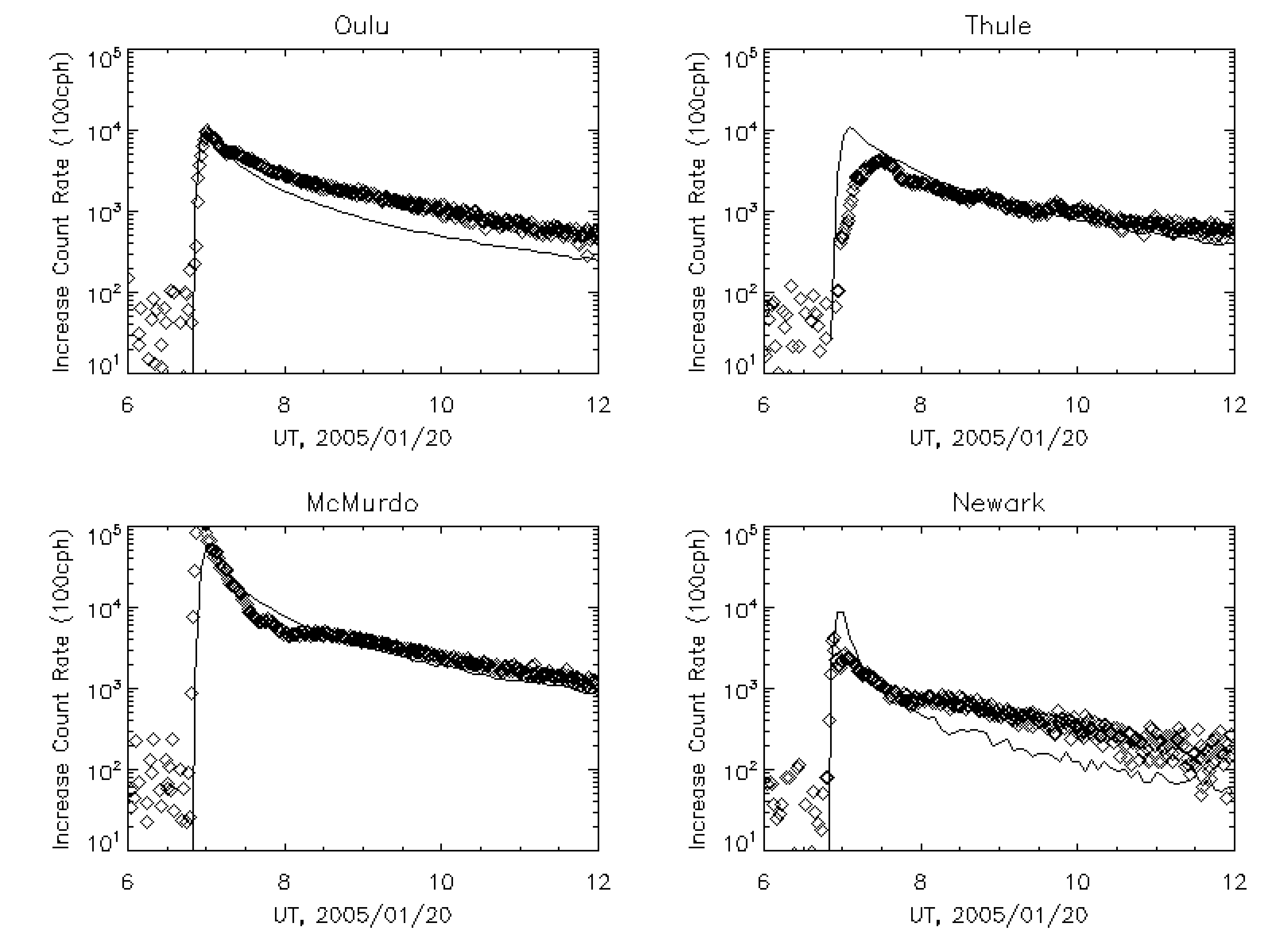
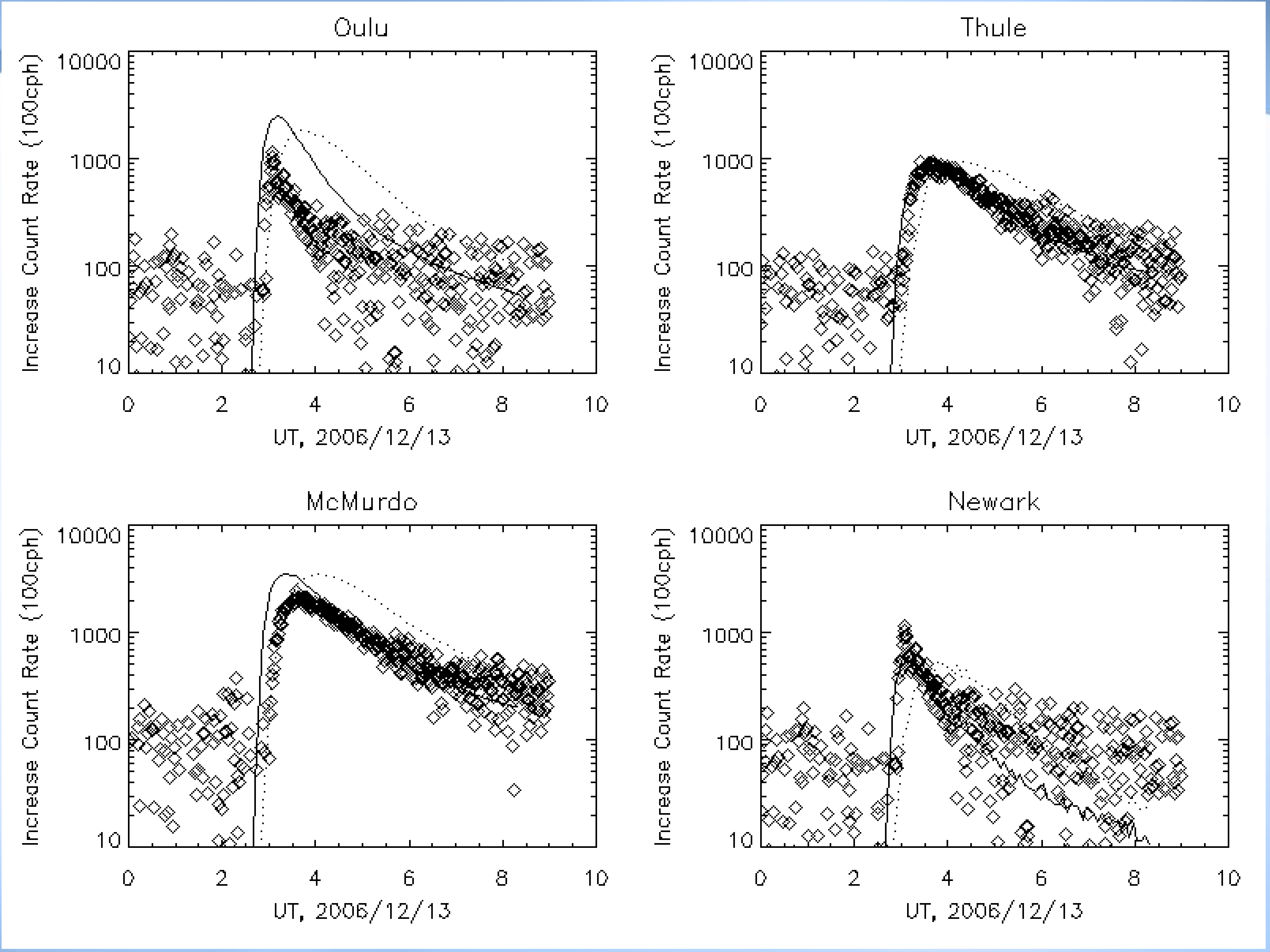
# Neutron count rate for GLE69



# Neutron count rate for GLE70



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# Summary

- We have developed WASAVIES (Warning System for Aviation Exposure to Solar Energetic Particles) to provide information to aircrews.

- In present status, WASAVIES is composed of three simulations, SEP transport in interplanetary space, SEP trace in magnetosphere, and air-shower in atmosphere.

- WASAVIES can roughly reproduce dose rate with typical parameter of spectrum index, mean free path, and solar wind speed, by only changing the time-scale of SEP injection profiles at the Sun.

- It is interesting to note that such a simple setting creates the wide varieties of GLEs.

# Future

- WASAVIES gives the simplest start point, and a lot of improvements are awaited.
  - Use CME shock parameter to calculate SEP injection spectrum.
  - Use solar wind simulation to reproduce interplanetary condition.
  - Implement the system into JISCARD-EX for operational use.
  - etc…

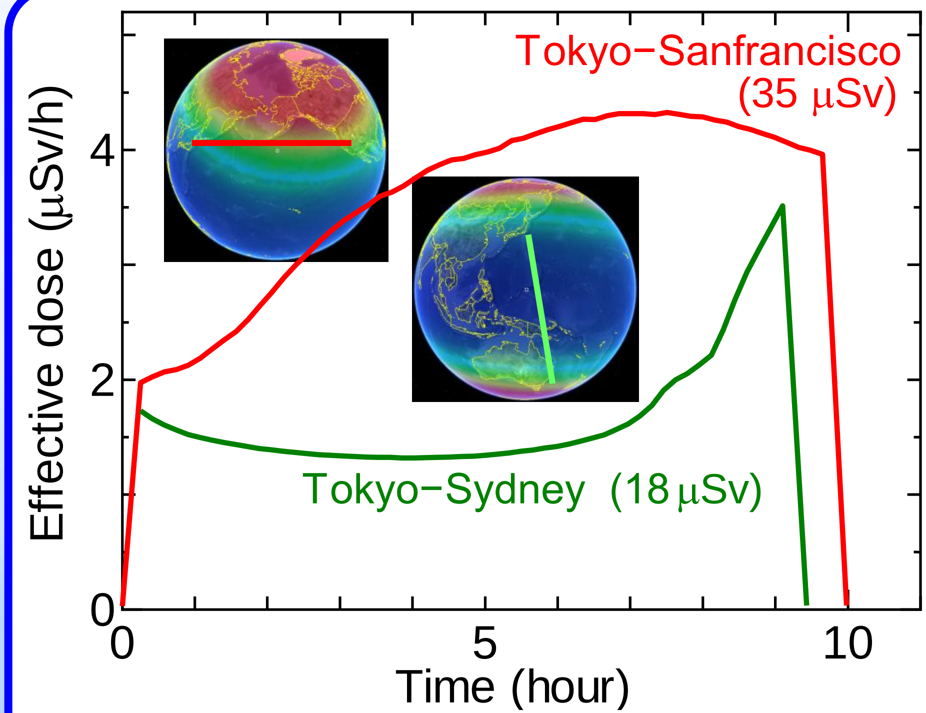
# JISCARD-EX

**Japanese Internet System for Calculating Route Dose**

http://www.nirs.go.jp/research/jiscard/ (in Japanese)

### Flight conditions
- Departure & arrival airports
- Date of the flight

### Estimation of Flight Route
- Latitude & longitude
- Flight altitude & duration




**Route-dose calculated by JISCARD-EX**

### Calculation of GCR doses on the flight route

**MAGNETOCOSMICS***

Vertical cut-off rigidity

**EXPACS**
- Terrestrial cosmic-ray flux
- Dose conversion coefficients
- Force field potential (NM data**)

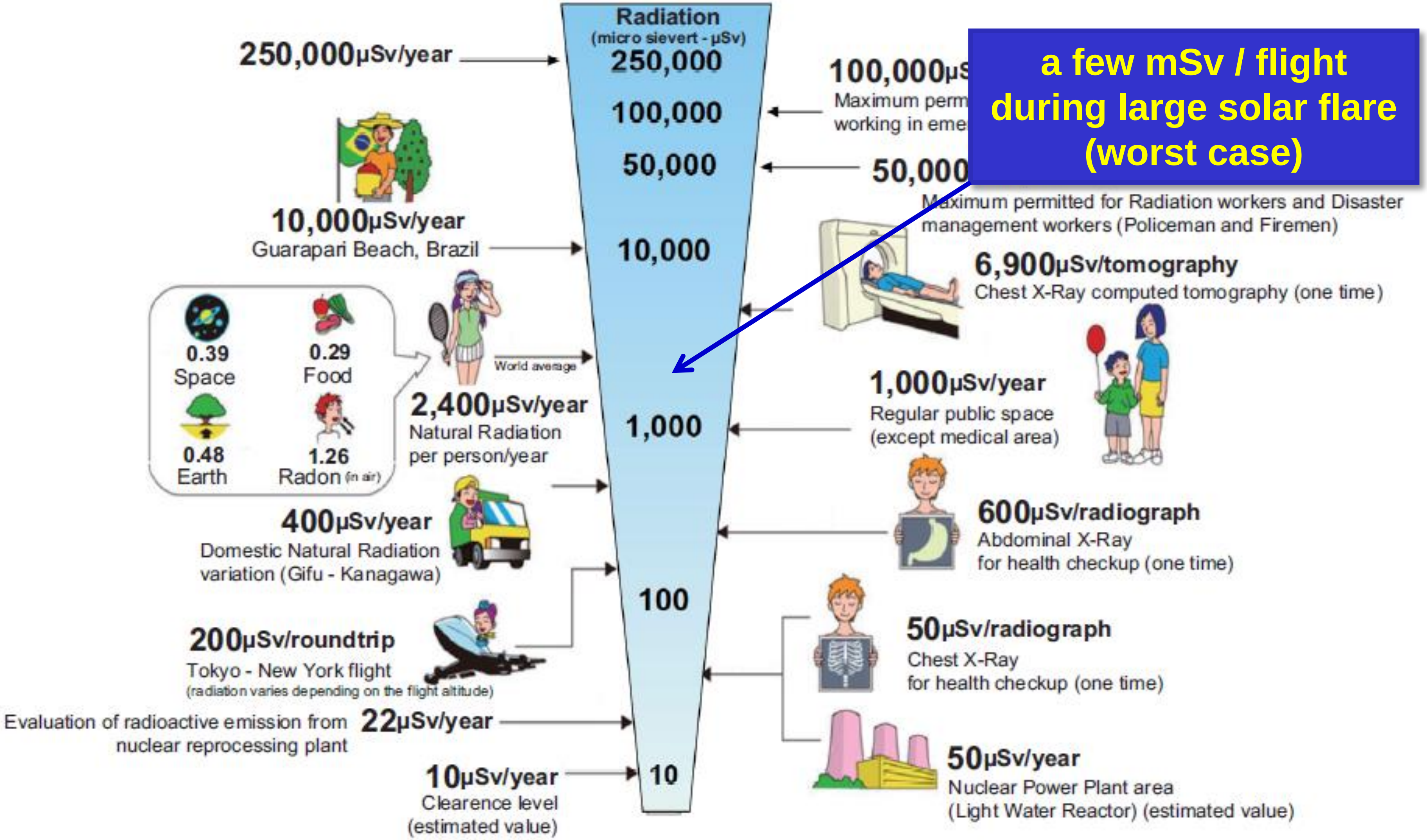
**Dose during the whole flight**

* http://cosray.unibe.ch/~laurent/magnetocosmics/

** http://neutronm.bartol.udel.edu/

# Thank you

# Radiation exposure level




**Radiation Exposure Level in Daily Life**

# Regulation of aircrew exposure

## International Committee on Radiological Protection (ICRP)

Aircrew exposure to cosmic-ray is recognized as an occupational hazard in 1990

## Each Country

Issued the regulation laws for the annual dose limitation of aircrews

### in Japan …

- Recommendation for the aircrew dose limitation (5 mSv/year) was issued in 2006
- It is desirable to forecast the aircrew doses during large solar flare using the latest knowledge of the space weather research, and make adequate actions to reduce the dose

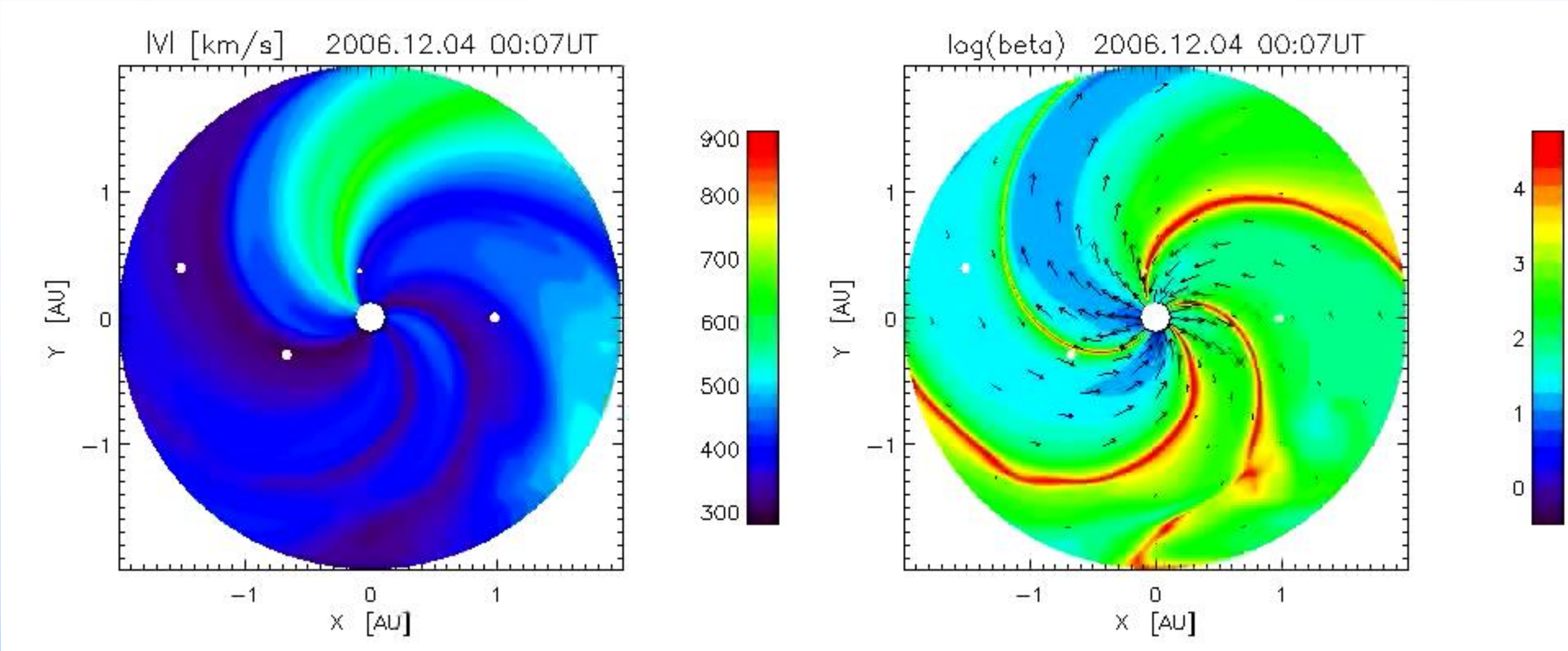
## Airline Companies

- Estimate the annual doses for their aircrews using various calculation codes

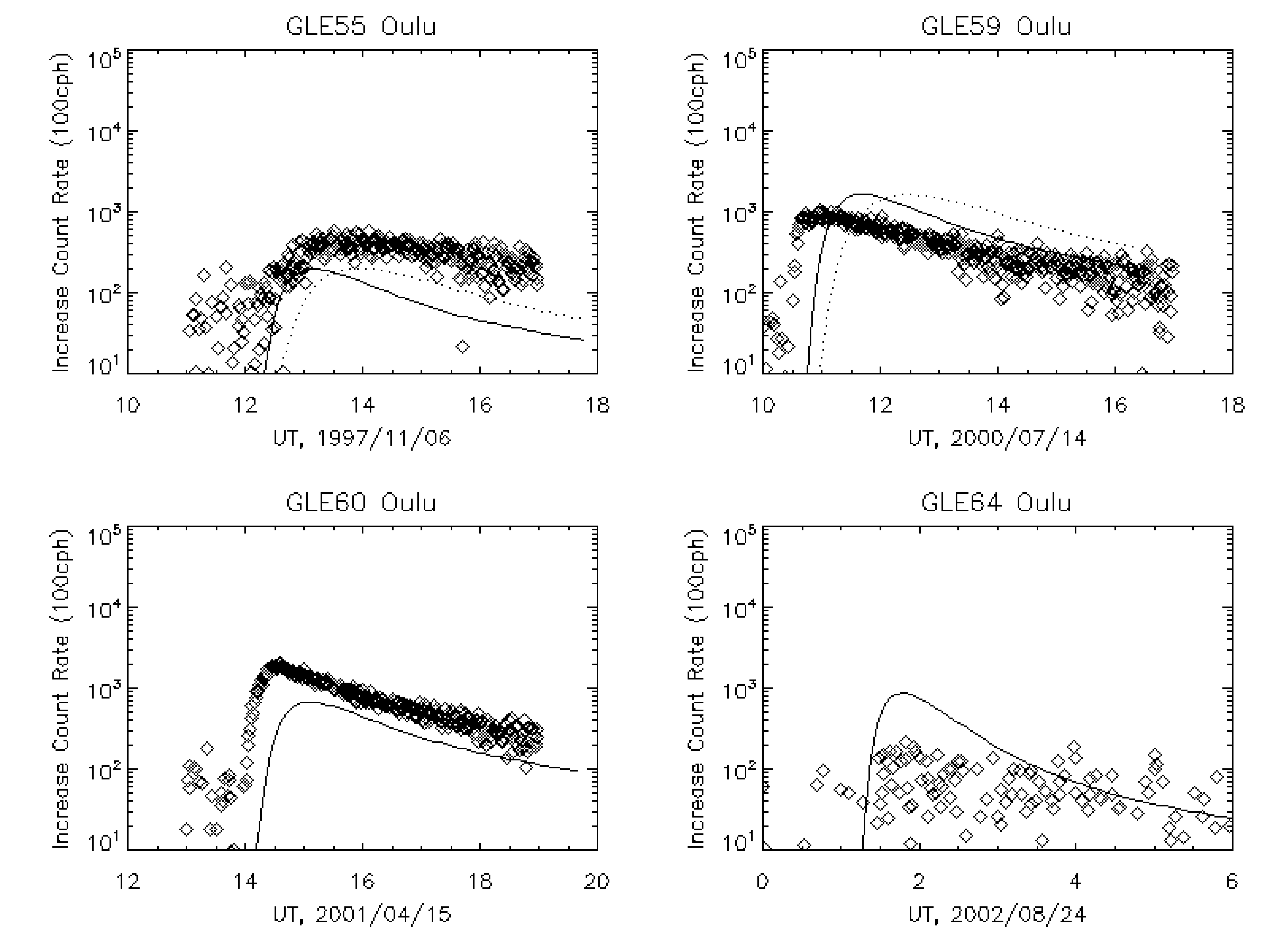
**JISCARD(Japan), CARI-6 (USA), EPCARD (Europe), PCAIRE (Canada)**

- Do nothing for the second term due to the difficulty of forecasting doses

# Solar wind and CME simulation



# Poorly reproduced case

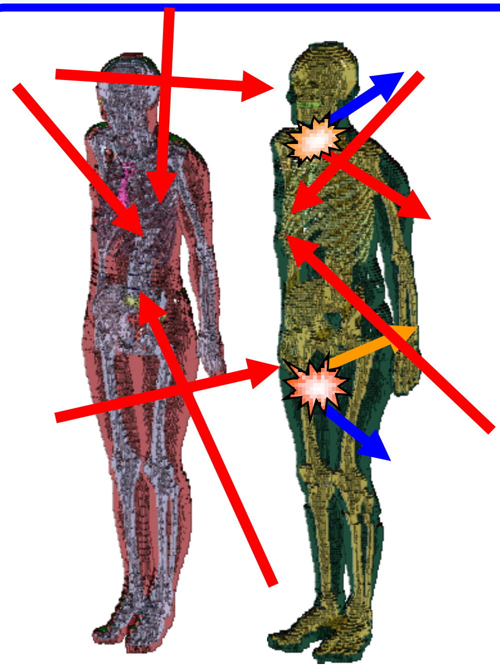


# Conversion from flux to dose

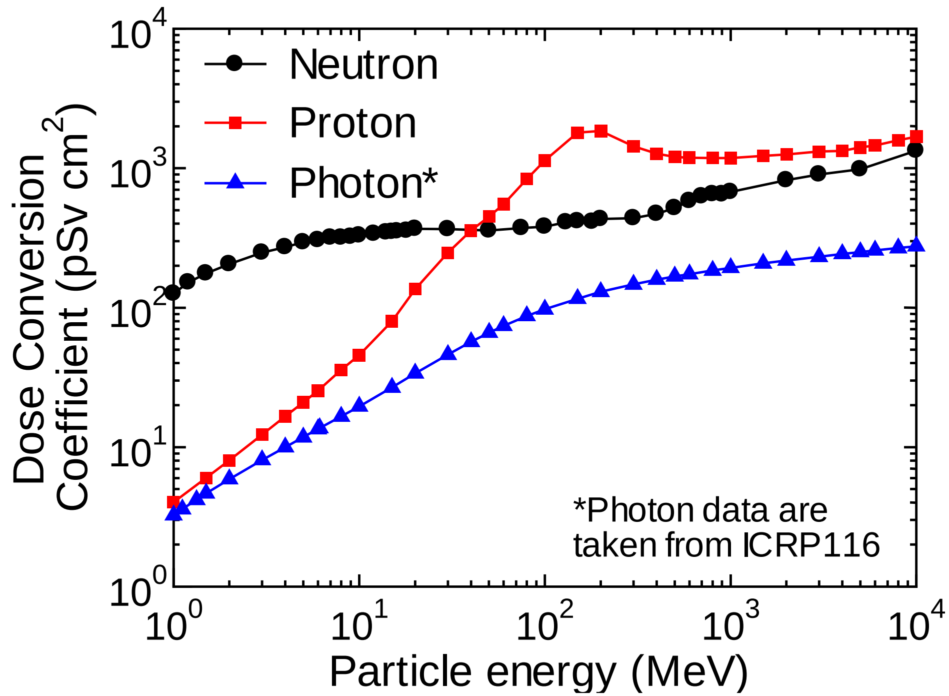
**Dose in human body ≠ Dose in the air**

**Aircrew dose = Cosmic-ray Flux × <u>Dose Conversion Coefficient</u>**

- Radiological impact to human body by unit-flux irradiation
- Calculated based on the PHITS simulation



**ICRP/ICRU adult reference computational phantoms**

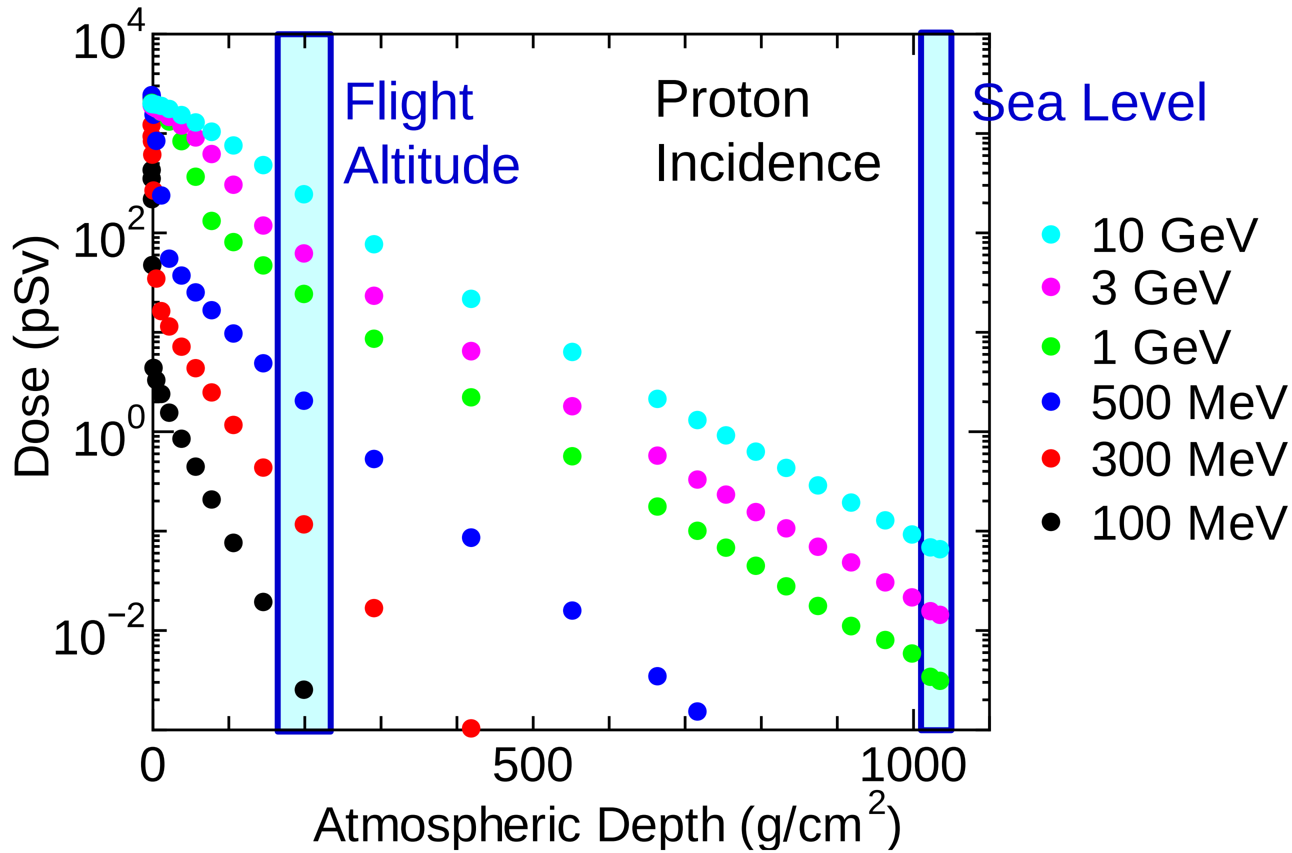



Dose Conversion Coefficient for ISO Irradiation

T. Sato et al. *Phys. Med. Biol*. **54**, 1997, (2009), T. Sato et al. *Phys. Med. Biol*. **55**, 2235, (2010)

# Conversion from flux to dose

**Aircrew dose = Cosmic-ray Flux × Dose Conversion Coefficient**




**Atmospheric depth-dependence of doses from mono-energetic irradiations**

- **Flight altitudes: Protons above a few 100 MeV can contribute**
- **Sea level: Only GeV-order protons can contribute**